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DYNAMIC INTERACTIONS BETWEEN IONOSPHERIC PLASMA AND SPACECRAFT

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ABSTRACT

In recent years, studies of the interactions between Space Station Freedom (SSF) and ionospheric plasma have led to an improved understanding of the dynamics of these interactions. Plasma currents from the ionosphere control surface potentials, but the charge stored across dielectric surfaces becomes an important consideration in predicting dynamics of arc development. Time scales for the resulting interactions can be scaled for specific circumstances. In addition, active surfaces such as antennae and switched solar array surfaces have fostered thought on the interactions of AC driven systems. These systems can, under certain conditions, give rise to radiation and enhanced sputtering of surfaces. This paper will review the work performed for the SSF program to understand the dynamics of spacecraft interactions, and will discuss implications to other spacecraft.

INTRODUCTION

During the previous decade, much work has been done to develop models to help understand and predict interactions between spacecraft and the plasma environment[1]. However, engineering level codes such as NASCAP/Geo and NASCAP/LEO tend to rely on evaluating or tracing the evolution to, equilibrium conditions and drawing conclusions based on relatively constant conditions. While it is recognised that charging conditions are dynamic, the tools tend to assume rapid establishment of equilibrium conditions[2,3]. However, with the development of new technologies for expensive spacecraft, and the need to predict and scale effects to new systems without extensive testing, it has become necessary to begin to study the dynamics of these interactions.

Early in the design of Space Station Freedom (SSF), issues of plasma were investigated with the objectives of designing a plasma compatible space platform, and providing a platform suitable for ionospheric studies[1]. However, during the several SSF redesigns and mission redefinitions, these issues were forgotten[4].

However after the decision to ground SSF to the negative side of the solar arrays, Ferguson et al. raised several plasma compatibility issues[4]. This led to the establishment of the SSF Grounding Tiger Team, which attempted to evaluate the impact of arcing on SSF[5]. While this work has raised additional questions for further research, it has also contributed to a better understanding of how spacecraft respond to various plasma interactions. As new technologies are applied to new spacecraft, in particular those performing various ionosphere investigations, some of these plasma compatibility issues may become relevant.

The purpose of this paper is to review some of the plasma compatibility issues raised in the course of the SSF investigations, and where possible discuss the dynamic characteristics of these effects, both to help spacecraft users better understand the implications of these effects on their measurements, and to suggest future directions for research in plasma-spacecraft interactions.

DISCUSSION

Interactions and Time Scales

If a spacecraft is not effectively 'grounded' to the ionosphere, fluctuations in spacecraft potential can occur on a variety of time scales, from DC to microseconds. There can be a DC offset driven by exposed portions of the power system, due to current density differences in positive and negative species. This is roughly driven by $\sqrt{T_e/T_i}$, where T_e refers to the electron temperature and T_i is the ion temperature. If the power generation system is sensitive to illumination (solar cells) there may be a voltage transient associated with entering and leaving eclipse. There may be transients associated with switching of systems on-board the spacecraft, for example solar array circuits, or operation of high voltage experiments. As the potential of the spacecraft changes, current is collected on the surface trying to bring the spacecraft back to equilibrium. In many cases the current collection mechanisms can be identified making it possible to estimate the times scale, and hence the frequency domain of the transients. We would like to be able to predict the magnitudes of some of these effects in order to assess their impact on measurements, or to justify requirements on spacecraft design.

In this work the term grounded is used in a couple of ways. The 'plasma ground' is used to describe the electrical connection between the spacecraft and the local environment, i.e. the ionospheric plasma. The 'spacecraft ground' refers to the internal process of referencing potentials to a common place on the spacecraft, usually the structure. This is comparable to a chassis ground.

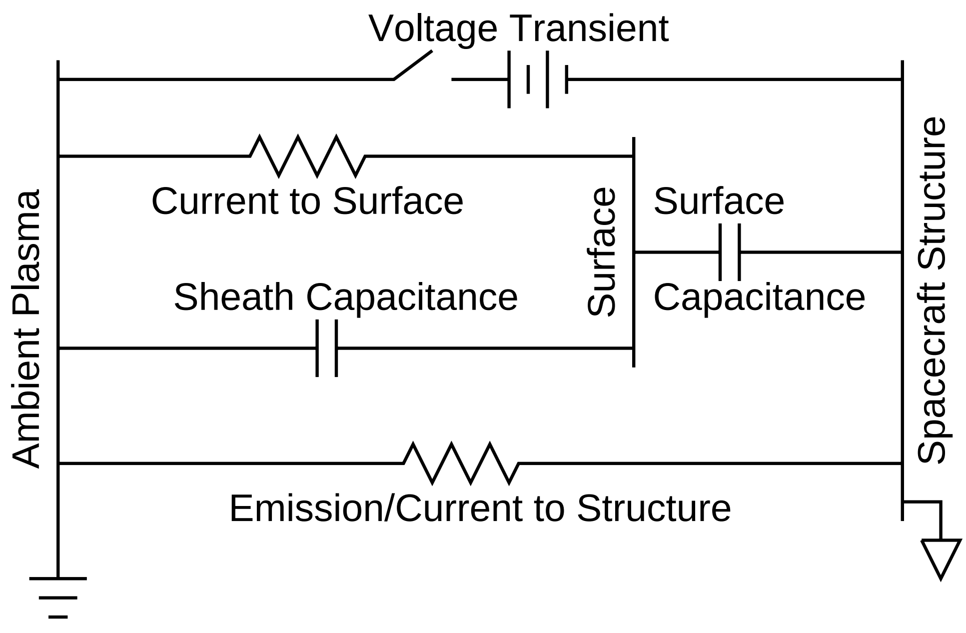

Figure 1. Spacecraft-Plasma Interaction Schematic Diagram.

To track the potential changes during transients it is helpful to look at a simplified description of the spacecraft-plasma interaction. Figure 1 shows a schematic diagram to illustrate this. The electric potential of the spacecraft can shift by changes in the energy or current of ion or electron collection, or electron emission. The capacitance of the spacecraft to plasma, or across a surface coating, plays an important role in determining the magnitude of the interaction, while the current collection and emission mechanisms then contribute to the time scale of the transient.

The capacitance of the spacecraft sheath tends to be much smaller than the capacitance of the surface. The sheath thickness tends to be fractions of a centimeter, thicker with high potentials, while dielectric materials on surfaces tend to be fractions of a millimeter. The dielectric constant of surface materials tend to be higher than that of vacuum also contributing to a higher capacitance. An interaction that occurs on a completely insulated satellite, for example a voltage shift due to auroral interactions, will involve relatively small currents even if large voltage excursions occur, because of the small capacitance. However, interactions that involve the spacecraft structure, for example arcing, can access the energy due to the relatively large dielectric capacitance of the surfaces.

Arcing

Transients due to arcing are of interest because (1) they may lead to damage of the affected surfaces or contamination of other spacecraft surfaces, and (2) they are probably the most severe cases of voltage change and time scale, aside from planned antenna use. Our interest has been more in how these transients may damage spacecraft than in how they effect measurements. However, these assessments illustrate some of the issues involved in evaluating the impact of other transient effects.

Arc Evolution Mechanism

There are several known mechanisms which can initiate an arc; dielectric breakdown[6], micrometeor and debris impact[7,8], solar cell (edges or interconnects) arcs[9]. The initiation mechanism is important to understanding some arc characteristics such as arc frequency and arc threshold potentials. However as will be seen later, if a large enough initiation event occurs and the substrate is biased negative relative to the ambient plasma, the evolution of the arc appears to be independent of the initiation mechanism[10]. The key common feature appears to be a substrate biased negative relative to the ambient plasma, covered or nearly surrounded by a dielectric layer. This produces electric fields which collect electrons on the dielectric surface and focus ions back to the metal or conductive arc surface. Three issues need to be addressed in an arc circuit mechanism; (1) Development of the arc plasma, (2) Transport of electron current to the surface, and (3) transport of current through the spacecraft. Figure 2 illustrates the hypothetical process.

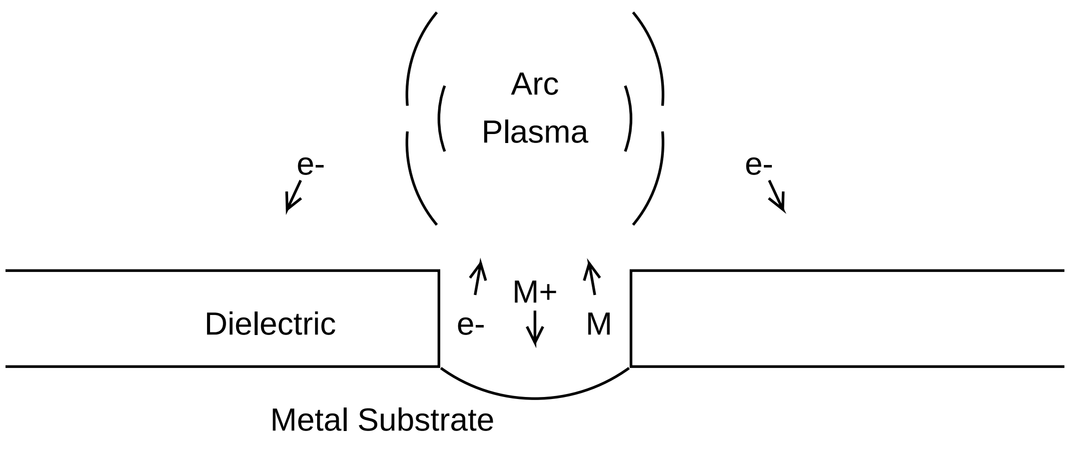

Figure 2. Proposed Arc Evolution Mechanism.

In this evolution model an initiation event provides an initial ignition plasma at the arc site and, if not already exposed, exposes the underlying conductor. Due to the dielectric material surrounding the arc site, a high electric field exists at the site, which focuses ions from the plasma back to the arc site. Bombardment of the site by the attracted ions may cause sputtering or sublimation of neutrals. Electrons can be emitted from the site by a combination of thermionic and field emission. If the collision lengths are such that the electrons can collect a few ten's of eV of energy, ionization may occur when they strike the emitted neutrals, thereby creating ions and sustaining the arc plasma.

As electrons are emitted from the arc site and arc plasma, the potential of the substrate rises. The potential of the dielectric surface also rises due to capacitive coupling with the substrate. The surface now collects electrons from both the arc plasma, or the ambient plasma. Since the capacitance to space is ordinarily much smaller than the capacitance across the dielectric, most of the potential change appears across the plasma sheath, the potential of the surface also rises. Then, as charge is attracted from the plasma, discharging the dielectric. If the arc continues on the time scale of the dielectric discharge, the energy available from the dielectric capacitance can continue to drive the arc.

The current available to drive the arc is limited by the ability of the spacecraft surfaces to collect current from the arc or ambient plasma. The arc source appears to be the principal limit on arc currents, from tenths of an amp for small capacitance systems[11] (few hundred picofarads), to a thousand amps for large capacitance systems[6] (a thousand microfarads). Unless provision is made in the design, spacecraft structure does not appear to affect arc development, except perhaps in the rise times. During the Electrical Grounding Tiger Team discussions, it was argued that spacecraft inductances might prevent arc development. But during tests, the inductance of the wiring and internal inductance of capacitors were not sufficient to prevent arcs nor did they obviously effect development. Arcs appear to develop slowly enough (microseconds) that inductive effects seem to be unimportant to the arc evolution.

So far it is assumed that the structure can return the current generated by the arc plasma. But what limits are there on the current that can move to the surface? Is this current sufficient to sustain an arc? Two independent mechanisms are examined for this part of the current loop. A lower bound on the current available can be estimated by the electron thermal current to the spacecraft, i.e. for large spacecraft, the product of the electron thermal current density with the spacecraft area. This is the current available to the spacecraft due to its changing voltage, neglecting geometric and plasma sheath considerations.

For normal spacecraft voltage shifts, this probe-like collection is the mechanism that governs current collection. But for arcs there is an additional source of current.

The second mechanism assumes that the current is due to the expansion of the plasma arc. Vaughn et al.[12] noted a delay in the plasma enhancement seen by a movable Langmuir probe. For their configuration (anodized aluminum biased to -240 V) they estimated a primary expansion velocity of about 3x10^4 m/sec. This model can be used to estimate the current due to an expanding arc plasma[13] of $I = CV dA/dt = 2\pi CVv$, were A is the dielectric area covered by the arc plasma, and v is the expansion velocity. This estimate represents an upper bound as it assumes that the coating capacitance is instantaneously and completely discharged as the arc plasma moves over it. However, this assumption will break down as the arc plasma density falls due to expansion. Eventually the density may fall sufficient to terminate the arc. This mechanism suggests a current limited by the expansion velocity of the arc plasma.

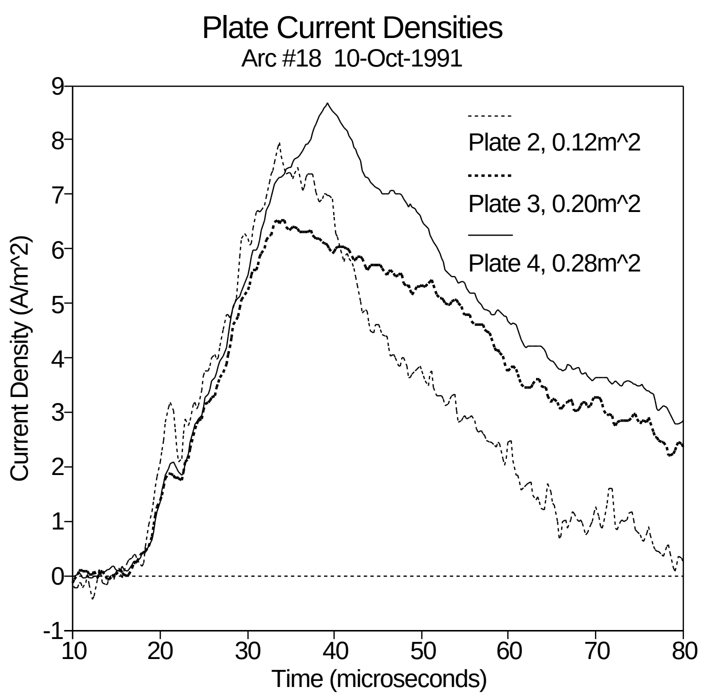

Figure 3. Arc Return Currents to a series of concentric rings.

A third mechanism related to the second may produce higher currents for microsecond time scales. On this time scale the ions near the 'old' plasma sheath edge have not had time to leave and form a new plasma sheath. So electrons from the arc plasma sheath are not space-charge-limited, at least in the usual sense of the term.

We have seen immediate increases in electron current on a distance scale of 1/2 meter on a sample made of several plates[14]. Figure 4 shows return currents during an arc on a set of concentric anodized aluminum rings. The total area of the sample was about 2 m^2. The arcs, instead of occuring on the center plate as intended, occured on the outside ring. In spite of the 3 to 4 meters of wire forming the electrical connection, currents arrived simultaniously at all the plates. The magnitude of the currents were approximatly proportional to the ring area.

Arc Magnitude, time scales

An obvious parameter for scaling ground based studies to spacecraft is the system capacitance. The capacitance together with the potential difference to plasma at the arc site determines the charge and energy available for a discharge, and how the electric fields associated with the arc event will evolve over time. This hypothesis suggests that it may be reasonable to study arcs from large space systems by simulating them with a comparable capacitance.

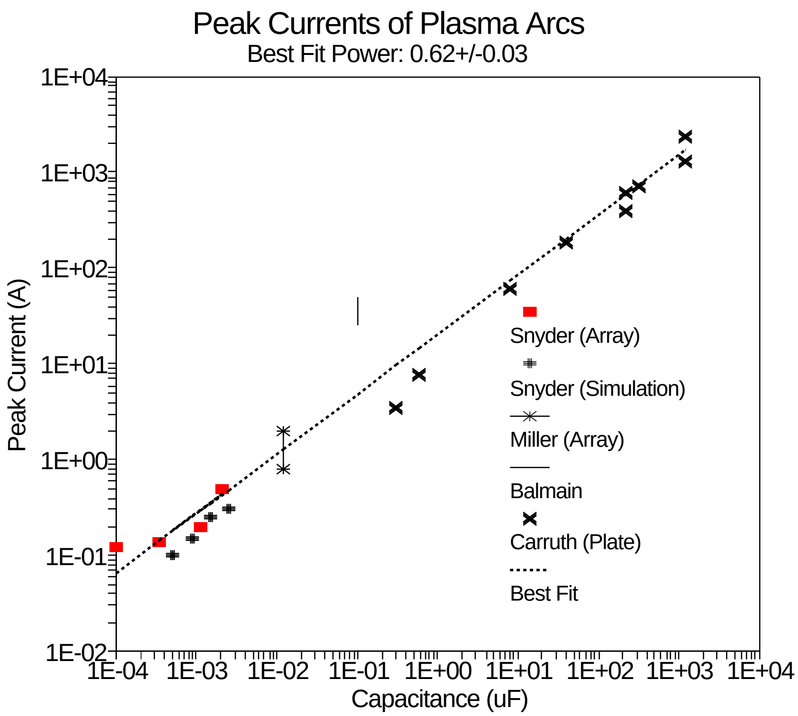

Figure 4. Observed Peak Arc Currents as a function of Capacitance.

Figure 4[10] illustrates an observed correlation between peak current and system capacitance. The peak current is an interesting parameter since it puts a lower bound on the duration of an arc, and on the magnitude of the EMI generated by the arc. The data is from a variety of sources[8,10,15–17]. During tests, wide variations in the peak currents are seen for a particular set of conditions. Calculated standard deviations of the peak currents are on the order of the average. Points in the figure generally indicate the average of a number of arcs, but sometimes a range is indicated instead. The data from Balmain[16] was for a Helium plasma at millitorr pressures.

Figure 5[10] shows the same sets of data plotted against energy instead of capacitance. The energy is calculated from $1/2CV_0^2$ where C is the capacitance and V_0 is the bias voltage. This introduces some dependence based on voltage. The high capacitance data was obtained in connection with space station tests at about 100 to 150 V while the low capacitance data was taken during studies of solar cell arcs with potentials closer to 1000 V. We note that the high capacitance data extrapolates to, and can be extrapolated from the low capacitance data. This is not quite the case when the energy data is examined. This suggests that capacitance maybe a better predictor of peak arc current than is energy. The increased voltage appears to extend the arc duration rather than increase the current.

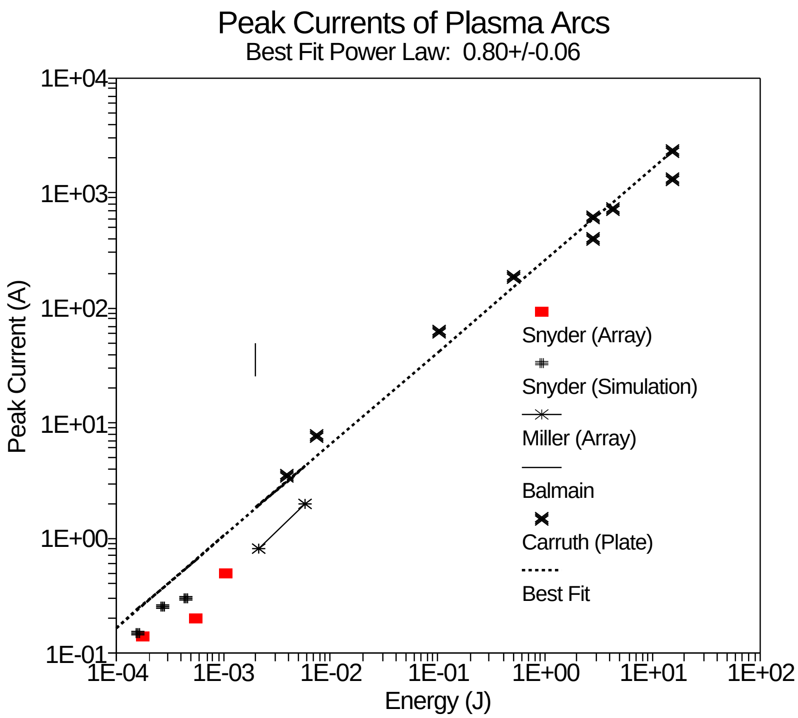

Figure 5. Observed Peak Arc Currents as a function of Energy.

As a working hypothesis we use the correlation between the peak arc current during an arc and the capacitance of the system to predict arc currents. But this hypothesis is not based on a rigorous arc model. Instead it is based on empirical observation. A correlation with bias voltage or energy stored in the system might be easier to understand. Development of a quantitative arc development model might suggest extrapolation procedure that could be used with more confidence.

The above technique is used as a way to estimate arc current to about a factor of two. Using the time to deplete the charge stored in the system permits an estimate of the arc duration, i.e. $\Delta t = C\Delta V/I_p$, where Δt is a lower bound on the arc duration, ΔV is the change in voltage during an arc, i.e. a material dependent cutoff voltage subtracted from the bias voltage, and I_p is the estimated peak current. In practice the current dies down with the substrate voltage, but this method permits an order of magnitude estimate, enough to see in what frequency regime interference might be expected.

Mitigation

Presently we suspect that there are material dependent voltage thresholds. For silicon cells these appear to about -200V for silicon solar cells [18], and about -50V for anodic oxide coated aluminum[14],and kapton covered copper[17]. The solar cell arc threshold is an empirical observation, but coincides with the voltage where arcs appear to shut off. The copper and kapton thresholds are based on arc shutoff potentials, but simulated debris hit induced arcs have been observed at 75V on aluminum[19], and one sample arced repeatedly at 50V[14].

Two types of systems can easily develop potentials significantly different from the ambient plasma. For large spacecraft vxB induced potentials can be significant, tens of volts for ISSA (International Space Station Alpha) sized structures. More commonly the spacecraft potential will be determined by exposed biased conductive surfaces such as solar cells, or other active equipment such as high voltage experiments. It may be possible to electrically isolate these systems from the spacecraft structure and the rest of the spacecraft if they would otherwise cause excessive potentials. However, it may be difficult to provide sufficient isolation. If it is necessary to ground to the structure and both positive and negative potentials are exposed, grounding to the positive side is preferred. It is typically the exposed surfaces that provide the electrical connection to the ambient plasma. Since the positive surfaces tend to collect electrons while negative surfaces tend to collect ions, the positive surfaces have less effective resistance to plasma. It will normally be prudent to ground the positive side to structure.

It is possible to provide an electrical connection to the ambient plasma on a negative ground spacecraft using a hollow cathode plasma contactor, or some other device capable of providing relatively large currents. This is the technique being used for ISSA, where it is anticipated that about an ampere of current will be driven through ground cables to control the spacecraft potential.

A/C Interactions

Most studies of plasma interactions typically assume that a system eventually reaches some equilibrium condition, i.e. conditions stop changing. This is obviously not true of systems with a driven component. However, systems that are periodic may achieve a steady state where the changes are repetitive. This can apply to AC (Alternating Current) power distribution systems, antennae, some active experiments, and solar array power control systems. The criteria for reaching a 'steady state' is that the net charge collected during a period is zero. If both secondary emission and backscatter collisions are negligible, the electrons collected during the positive part of the cycle will be equal to the ion collection during the negative part. Except for very low frequencies, this tends to drive the system negative until the maximum negative potential on a dielectric surface is nearly twice the amplitude of the driving oscillation.

Our main concern has been that sputtering rates may be higher than expected due to ion collection at energies higher than otherwise anticipated. In fact this technique is commonly used at much higher plasma densities, voltages and frequencies to sputter dielectrics in plasma reactors. The effect may be particularly important in low earth orbit where thin atomic oxygen resistant coats may be sputtered away exposing underlying polymers to attack. Kennedy[20] has documented this sputtering for ionosphere-like conditions. However, even under more benign circumstances the effect may be of interest to experimenters as it results in larger plasma sheaths than otherwise anticipated and may cause significant fluctuations in spacecraft potential. It is conceivable that in extreme cases the spacecraft potential could fluctuate relative to plasma, disturbing some measurements.

Mechanism: AC Surface Potentials

Figure 6 shows the circuit diagram used to calculate the potential of the surface[21]. $V_a(t)$ is the electric potential of a driving conductor measured with respect to plasma and $V_s(t)$ is the potential of the surface with respect to plasma. C_1 is the capacitance between the driving conductor and the exposed surface. This will be related to the dielectric coating of the surface but may include other artificial capacitances between the underlying conductor at the surface and the power system or other power sources. $C_p(V_s)$ is the effective capacitance between the surface and the plasma. In general this will depend on the plasma sheath thickness, and will vary with surface potential. For the case of a weak plasma this will be small and the surface potential will be near the driving voltage. However, for high density plasma and thin plasma sheath, especially when the capacitive coupling of the surface to the driving conductor is weak, C_p may be important and the surface potential will be some fraction of the driving potential. $I(V_s)$ is the current from plasma to the surface and may be obtained from probe theory.

Since the displacement current through C_1 is equal to the displacement current plus the probe collection current through the sheath,

$$\frac{d}{dt}C_1\big(V_a(t) - V_s(t)\big) = I(V_s) + \frac{d}{dt}C_p(V_s)V_s(t). \tag{1}$$

From equation (1) the rate of change of the surface potential can be obtained,

$$\frac{dV_s}{dt} = \frac{\frac{dV_a}{dt} - \frac{I(V_s)}{C_1}}{1 + \frac{1}{C_1}\frac{d}{dV_s}C_p(V_s)V_s}. \tag{2}$$

Note that the factor dC_pV_s/dV_s is an effective capacitance of the plasma sheath. If C_p is independent of V_s, it reduces to C_p.

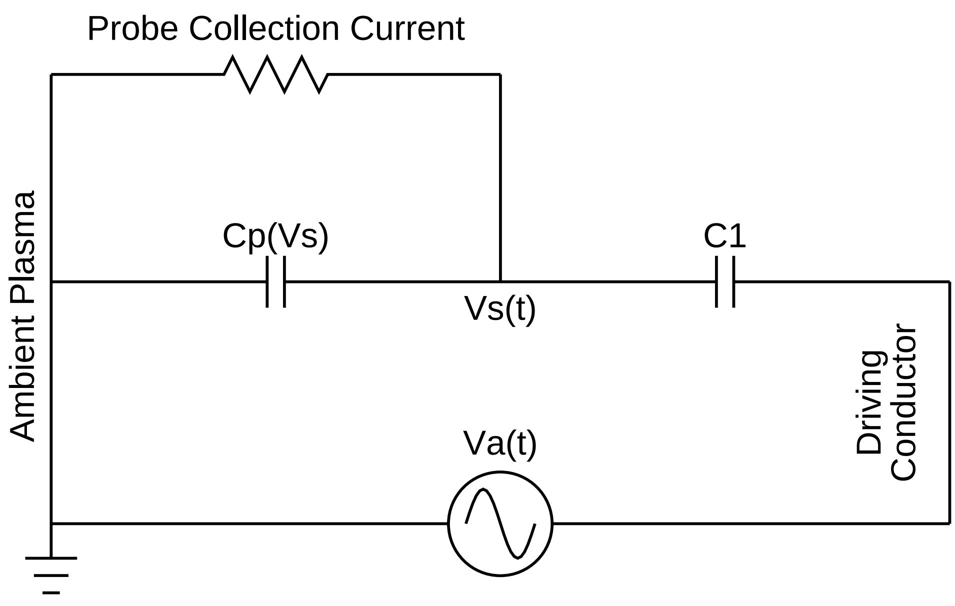

Figure 6. Circuit diagram to evaluate Surface Potential, V_s.

The capacitive term in the denominator is due to the voltage dividing effect of the two capacitances C_1 and C_p. Normally C_1 will be much greater than C_p, since C_1 is usually due to thin dielectric films and C_p has a minimum thickness of the plasma debye length (i.e. cm scale lengths). Thus the capacitive term will be negligible, and the surface potential, V_s will tend to track the driving potential, V_a.

The current term in the numerator serves to bring the surface toward plasma ground. If $V_a(t) = V_0 exp(i\omega t)$, the magnitude of dVa/dt will be on the order of $V_0\omega$, where V_0 is the amplitude of the driving voltage and ω is the angular frequency. If I/C_1 is much larger than this, the surface is effectively shorted to plasma ground. In practice, however, the plasma current term will be smaller than $V_0\omega$, and instead this term determines a) what the time average of the surface potential is, and b) how long it takes to get there.

Multiplying equation (2) by the denominator of the right side and integrating over from t_0 to t gives,

$$V_s(t)\Big[1 + \frac{C_p(V_s(t))}{C_1}\Big] - V_s(t_0)\Big[1 + \frac{C_p(V_s(t_0))}{C_1}\Big] = \big(V_a(t) - V_a(t_0)\big) - \int_{t_0}^{t} \frac{I(V_s)}{C_1}dt. \tag{3}$$

An equilibrium condition is reached, i.e. $V_s(t) - V_s(t_0) = 0$, for periodic V_a, i.e. $V_a(t) - V_a(t_0) = 0$, when the charge collected over a cycle, $\int_t^{t+\tau} I(V_s)dt$, is zero. Since electron current densities tend to be much higher than ion current densities in ionospheric plasmas, V_s will charge somewhat over each cycle resulting in a increase in the ion collecting part of the cycle at the expense of the electron collecting part, for high enough frequencies. This continues until V_s is nearly offset by $-V_0$, so that V_s varies from a small positive value to nearly $-2V_0$.

The long term behavior can be discussed by examining the change in Vs over one period, τ, of the driving voltage. Equation 3 becomes instead,

$$V_s(t+\tau)\Big[1 - \frac{C_p(V_s(t+\tau))}{C_1}\Big] - V_s(t)\Big[1 - \frac{C_p(V_s(t))}{C_1}\Big] = -\int_t^{t+\tau} \frac{I(V_s(t'))}{C_1} dt'. \tag{4}$$

If V_s changes so little over one period that $C_p(t_0 + \tau)$ is nearly the same as $C_p(t_0)$, then

$$V_s(t_0 + \tau) - V_s(t_0) = -\int_{t_0}^{t_0+\tau} \frac{I(V_s(t'))dt'}{C_1 + C_p(V_s(t'))}. \tag{5}$$

Here, it can easily be seen that V_s will settle to an equilibrium condition once the charge accumulated over a cycle is zero. If $\langle I(t) \rangle$ is defined as $\big(q(t+\tau) - q(t)\big)/\tau$, then

$$\frac{\Delta V_s(t)}{\tau} = \frac{\langle I(t) \rangle}{C_1 + C_p(V_s(t))}, \tag{6}$$

which suggests that for high driving frequencies, where $V_0\omega$ is much greater than the maximum probe currents, the long term behavior of V_s ignoring the driving oscillations can be described by

$$\frac{dV_s(t)}{dt} = \frac{\langle I(t) \rangle}{C_1 + C_p(V_s(t))}. \tag{7}$$

Flat Plate

Some implications of this model can be examined for a simplified case of a flat plate driven by a sinusoidal voltage. For this example edge effects and details of how the plasma sheath grows will be ignored. It is assumed that for positive potentials the surface collects electrons at their thermal current density, and at negative potentials the surface collects ions at their thermal current density. Figure 7 illustrates the three applicable frequency regimes. It was generated from the results from a computer model which integrated the collected current to track the surface potential. The electron current density, J_e for this case is -1.2x10^{-4} A/m^2 and the ion current density J_i is 4.9x10^{-7} A/m^2. The capacitance, C_1, is 4.4x10^{-8} F/m^2, and C_p is considered to be negligible.

The three frequency regimes are determined by a comparison of amplitude of the rate of change of the driving voltage ($V_0\omega$) with the thermal current density. At low frequencies $C_1 dV_a/dt$ is always less than the ion current density and the plasma can always supply enough current to keep the surface at 0 V. Once $C_1 dV_a/dt$ exceeds the ion current density then the surface can begin to develop negative voltages, and the average voltage begins to drop. At high frequencies, where the RMS current is saturated, the driving voltage changes rapidly enough that it is always collecting either the full electron current density or the full ion current density. For this flat plate case the steady-state charging condition dictates that ratio of time spent positive (electron collecting) to that spent negative (ion collecting) is the ratio J_i/J_e. For this case, only 4.1x10^{-3} of the cycle is spent with a positive surface. For the rest of the cycle the surface is negative, collecting ions, and the maximum negative potential attained is only slightly less that $-2V_0$.

At extremely high frequencies, near or above the sheath formation times, the mechanism for the transport of charge as the sheath develops becomes important and the above model does not hold.

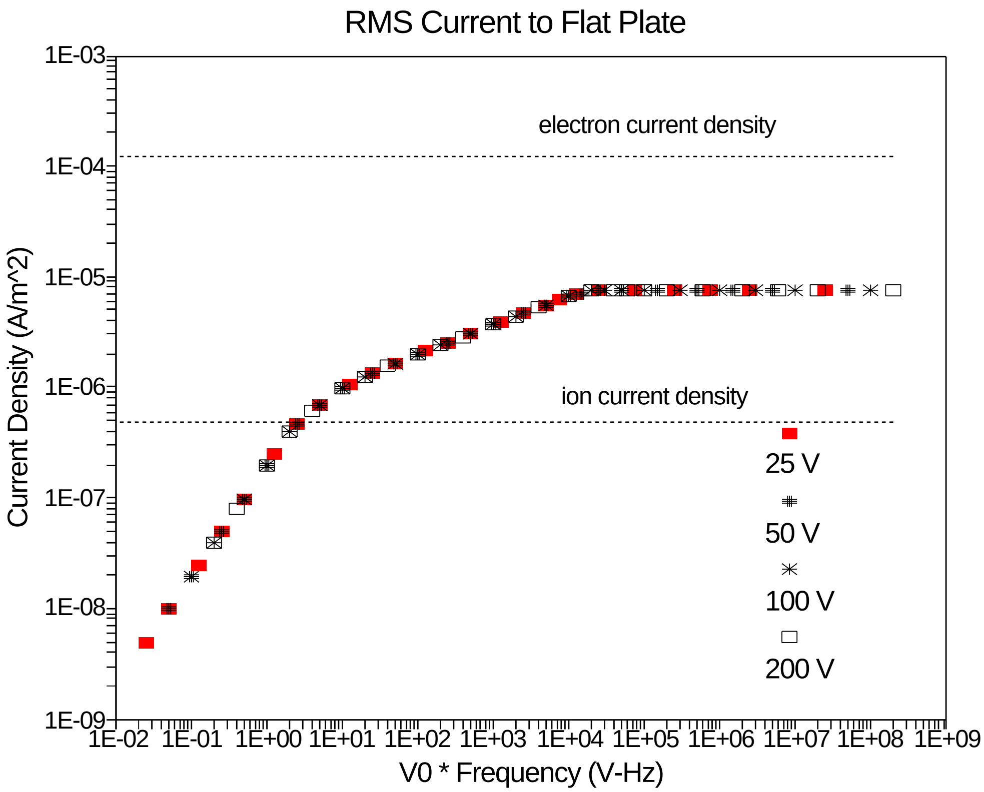

Figure 7. Root-Mean-Squared (RMS) currents to a flat plate.

Mitigation

The level of attention paid to addressing these issues will be mission and system dependent. Effects from some systems such as antennae will simply have to be tolerated. Hopefully antenna operate at frequencies high enough that the above analysis is not applicable. Sensitive equipment should be placed far enough away that they will not see the plasma sheaths from this equipment. Cables should be shielded, if not individually, at least collectively so the plasma does not see and react to them.

It may be possible to reduce fluctuations in spacecraft potential by including some kind of plasma contactor, i.e. a small electron emitter, to reduce the negative excursions.

CONCLUSIONS

An understanding of dynamic interactions with ionospheric plasma is beginning to be developed. The issues related to arcing are still quite controversial. This work has looked at some of the issues related to developing and sustaining arcs in ionospheric conditions. It has also presented a technique for estimating the amplitude and duration of arcs. This technique uses the capacitance of the system to estimate the peak current, and then uses the charge stored to estimate the duration of an arc.

In addition, as new technologies are implemented on spacecraft, new issues of environmental compatibility will arise. This work has also looked at some of the issues related to driving dielectric surfaces with

AC voltages. The steady-state charging criteria developed is that over an oscillation the ion charge collected is compensated for by the electron charge collected. This tends to drive the average potential negative, so that only for a small portion of the cycle is the dielectric surface positive.

The material discussed here only begins to touch on the issues related to dynamic interactions that will at least affect experiment operations and, if due care is not taken, may affect spacecraft reliability and lifetimes. Some of the work presented here is somewhat speculative, but may suggest ideas and hypotheses for future experimental and theoretical work.

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FIGURE CAPTIONS

Figure 1. Spacecraft-Plasma Interaction Schematic Diagram.

Figure 2. Proposed Arc Evolution Mechanism.

Figure 3. Arc Return Currents to a Series of Concentric Rings.

Figure 4. Observed Peak Arc Currents as a Function of Capacitance.

Figure 5. Observed Peak Arc Currents as a Function of Energy.

Figure 6. Schematic Diagram of Circuit to Evaluate Surface Potentials, V_s.

Figure 7. Root-Mean-Squared (RMS) Currents to a Flat Plate.